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ONE-DIMENSIONAL SEISMIC ENERGY TRANSMISSION ALONG HETEROGENEOUS LAYERED SOIL

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Abstract— **In this present study an initiative has been taken to find out the modification in the seismic energy along distance its travel because of the soil heterogeneity. Soil heterogeneity is considered here in one dimensional analysis and analyses were performed using software DEEPSOIL. Both equivalent linear and nonlinear analyses were performed on homogenous and heterogeneous soil models: uniform loose sand, uniform soft clay and layered soil deposit of sandwiched clay layer between loose sandy soils. The performances of these soil models are compared here in terms of peak ground acceleration (PGA) value, and seismic energy migration in terms of Arias Intensity (AI) evolution along the depth inside the soil deposit. It is observed from the analysis that, less seismic energy and PGA is developed in the heterogeneous soil than that in homogeneous soil. This is because during earthquake more softening is taking place in the layered soil than that in uniform soil. Further in this paper the requirement of nonlinear analysis over the equivalent linear analysis is also presented.**

Keywords— **Equivalent linear analysis, soil heterogeneity, nonlinear analysis, seismic energy migration.**

I. INTRODUCTION

Natural disasters such as earthquake, flood, volcanic eruption etc can physically as well as financially damage any country. Among them earthquake is an event which has very sudden occurrence and causes damage of lives and structures. In the recent Nepal earthquake (May 2015; Magnitude 7.3), the amount of loss of property in its capital only was more than 500 billion. This information is showing the devastation and brutality of such disaster. According to Charles Scawthorn, earthquakes are naturally occurring broad-banded vibratory ground motions. Earthquake occurs due to a number of phenomena such as plate movement, volcanism, landslides, rock bursts, and human-made explosions. Tectonic-related earthquakes are larger in magnitude and most damageable to structure. The Himalayan region falls in zone five as per seismic zonation and is very prone to earthquakes because of collision and tectonic movement of Eurasia and Indian plate and Indo-Burmese plate [1]. The performances of the structures during earthquakes depend on foundation which is interlinked with seismic interactive response of the surrounding soil. To assure performance based design the knowledge of seismic response of surrounding soil is also required, which basically changes with the change in ground condition. As the soil properties vary in both horizontal and vertical directions, it makes the behavior of soil complex under both static as well as in dynamic type of loads. Various studies have been done for assessment of soil seismic response for different site specific ground condition. Govindaraju and Bhattacharyya (2012) did the assessment for Kolkata city [2]. Kumar et al. (2014) did the assessment numerically for the area where the earthquake occurred earlier in Guwahati city by using field properties of soil [3]. Karimi and Dashti (2015) presented the performance of layered soil using physical and numerical modeling [4]. Chakrabortty and Popescu (2012) presented some experimental and numerical modeling on uniform and heterogeneous soil [5]. It was concluded from these studies that soil heterogeneity adversely affecting the seismic performance. All these studies show how ground condition, method of analysis etc. affect the seismic response of soil.

The nonlinear parameters of soil are calibrated based on the values in the literature and response in homogenous soil model. The numerical study is performed using the software DEEPSOIL. Two types of soil (loose sand and soft marine clay) are considered in this study. Chi-Chi motion is used as input motion for calibration of nonlinear parameter. It is observed that if the calibration is done properly then they provide same output at a particular depth for same model with various layer thicknesses. It is concluded that decrease in layer thickness upto a certain limit gives more accurate seismic response and after the limit it shows similar response for different thickness. Further the behavior of a particular soil and soil with varying properties are observed from layered analytical soil models. The effect of various methods such as equivalent linear analysis (ELA) which basically works in frequency domain and did total stress analysis, nonlinear analysis (NLA) which uses the effective stress analysis and works in time domain are also examined. The result also shows the importance of using nonlinear analysis over equivalent linear analysis.

II. MATERIAL PARAMETER

A. *Soft marine clay*

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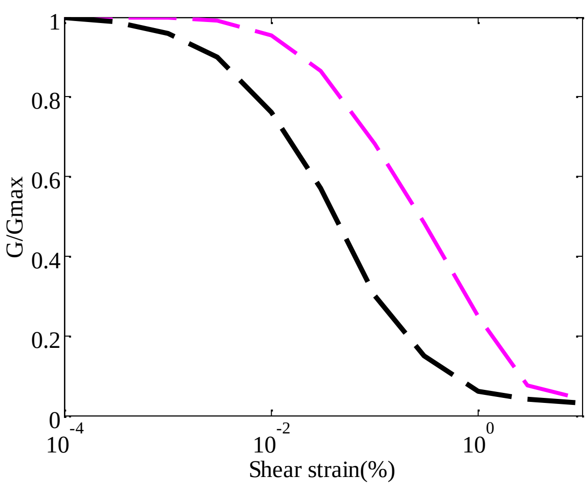
The homogeneous soil model (model 1) is used to calibrate the nonlinear parameter. For the soft clay soil model the authors take the reference of Venezuela North Paria clay or VNP clay which has over-consolidation ratio 1.0 [6]. The unit weight of the soft clay soil is 15.5kN/m^3 [7] and the shear modulus is taken as 13.75MPa [8]. For the curves for change in shear modulus and damping ratio with the change in strain, the curves suggested by Vucetic and Dobry (1991)[9] for normally and over consolidated soil with plasticity index value of 50 are taken by the authors in ELA. In NLA the same curves are used by authors for damping ratio and shear modulus value. The nonlinear parameters used in both method such as beta, s, p_1, p_2, p_3 are chosen in such way that the material curve tries to follow the reference curve suggested by Vucetic and Dobry (1991). The reference shear modulus degradation curves and damping curves for various types of soils are shown in Fig. 1 and Fig. 2 respectively. The nonlinear parameters b and d are taken as zero as authors assume that the analysis is pressure independent. The value of reference stress is taken as 0.18Mpa [9].

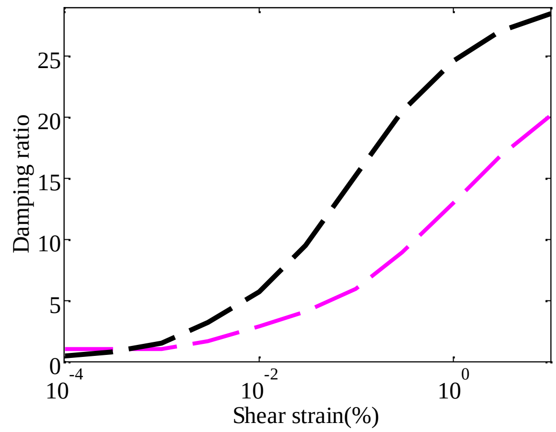


Reference curve for clay (Vucetic, 1991)
Reference curve for loose sand (Seed and Idriss, 1991, mean limit)

Fig. 1. Shear modulus degradation curves (G/G_{max} vs shear strain) for various soils

B. Loose sand

For analytical loose sand model the reference of Herber road site sand (Point Bar, PB) is used which has 15% fines content and has a relative density 45%. The sand is used by N. Matasovic in the investigation of liquefiable sands in various publications. The shear modulus value of the sand is taken as 61.43MPa [10]. The dry unit weight for the soil is taken as 15.5kN/m^3 [11]. For the damping ratio and shear modulus curve authors take the reference curves suggested by Seed and Idriss (1991) [12]. The nonlinear parameters used in both method such as beta, s, p_1, p_2, p_3 are chosen in such way that the material curve tries to follow the reference



Reference curve for clay (Vucetic and Dobry, 1991)
Reference curve for loose sand (Seed and Idriss, 1991, mean limit)

Fig. 2. Damping curves (damping ratio vs shear strain) for various soils

curve suggested by Seed and Idriss (1991) [9]and also the curve proposed in pressure dependent modified Kodner Zelesko (MKZ) model for PB sand.

III. Various Soil Models

The uniform layer of soft marine clay and uniform loose sand deposit of a total depth of 30 m was considered in the

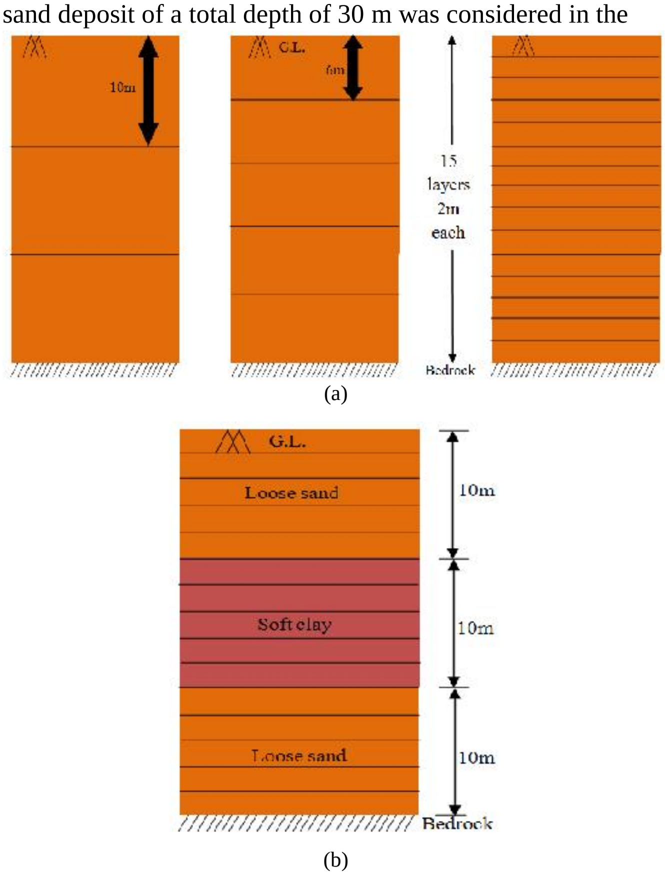


Fig. 3. (a) Model 1 (uniform layer of soft marine clay) and Model 2 (uniform layer of loose sand) subdivided into equal thickness of 3 layers, 5 layers and

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15 layers, (b) Model 3: layered soil (clay layer sandwiched between loose sandy soils)

analysis as Model 1 and Model 2 respectively. These models are further subdivided into 3 layers, 5 layers and 15 layers as shown in Fig. 3(a) during analyses to find out the optimum number of soil layers. In the heterogeneous layered soil model the layer of soft marine clay was sandwiched between loose sandy soils which are shown in Fig. 3(b).

IV. DEEPSOIL AS A TOOL FOR 1D SEISMIC ANALYSIS OR SOFTWARE USED

In numerical analyses for determining the seismic response of soil, the analytical soil model is considered either as a lumped mass model with multiple degrees of freedom or as a continuum discretized into finite elements with distributed mass [13]. In this study, an open source software DEEPSOIL was used for seismic response analysis of one dimensional soil column which include both ELA and NLA [14]. In DEEPSOIL, the soil mass is considered as a multiple degree of freedom lumped mass model system and the shear waves propagating through soil is assumed as vertically propagated horizontal shear waves [13]. In lumped mass model the soil is considered as a kelvin-vigot material where the both elasticity and viscosity work, which is shown in Fig. 4. In lumped mass model analyzer has to provide the shear modulus and unit weight for each of the soil layer and the model consider it in terms of elasticity and viscosity. Equivalent linear analysis is an iterative procedure. The damping ratio have been updated every time against the maximum strain obtain from the analysis, till the value of maximum shear strain remain same as the previous one. The following equation of effective strain used for the calculation

$$\gamma_{eff}=\gamma_{ref}*\gamma_{max} \quad (1)$$

Where, γ_{eff} denotes the effective shear strain, γ_{ref} denotes the reference strain and γ_{max} denotes the maximum shear strain.

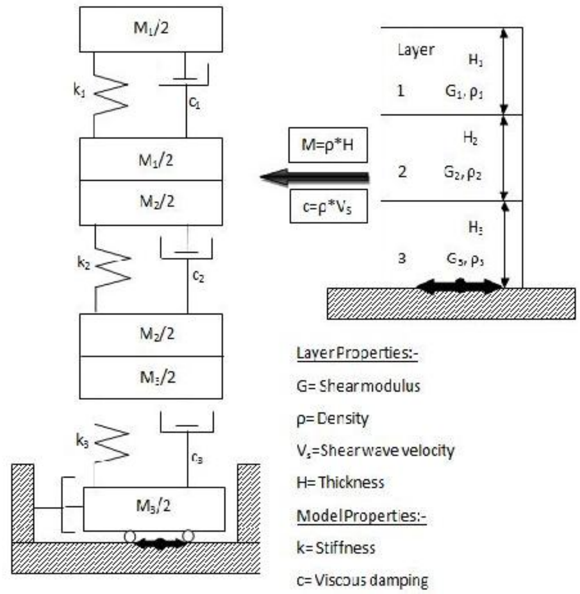

Fig. 4. Lumped mass model considering multi degree of freedom and also vertically propagated horizontal shear waves

In the nonlinear analysis the following dynamic equation has to solve [13],

$$[M]\{\ddot{u}\}+[c]\{\dot{u}\}+[k]\{u\}=-[M]\{I\}\ddot{u}_g \quad (2)$$

Where, [M] is the mass matrix, [c] is the viscous damping matrix, [k] is the stiffness matrix,$\{\ddot{u}\}$ is the vector of nodal relative acceleration,$\{\dot{u}\}$ is the vector of nodal relative velocity, {u} is the vector of nodal relative displacement, and $\{\ddot{u}_g\}$ is the acceleration at the base of the soil column and {I} is the unit vector.

The motion is recorded at a depth in the borehole, so within motion is applied at the base of the soil in bedrock. And the bedrock performs as a rigid base [15].

V. RESULT AND DISCUSSION

As discussed earlier, two homogeneous and one layered soil models were considered in this study. The Chi Chi motion which recorded in Taiwan 21st september1999 was applied as within motion. The frequency independent viscous damping formulation and frequency independent complex shear modulus formulation with effective shear strain ratio of 0.65 was used in ELA. In NLA same viscous damping formulation was used. The zero padded frequency domain interpolation was used for time history interpolation. The step control was flexible and maximum strain increment was 0.005 in time domain. The parameter used in DEEPSOIL for sand and clay are calibrated based on the PGA results of uniform soil.

After analyzing all the homogeneous models, it was found that decrease in the thickness of layer or dividing a deposit in more layers give better result up to a certain limit. Beyond this there is no change in the predicted responses.

This effect of number of layer is shown here for absolute maximum shear strain at midpoint of the layer (Fig. 5). It was observed from the results that for the model with overall thickness of 30 m, there is no change in maximum shear strain

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value beyond 15 layers. So, 15 layers in each models was used in further analyses.

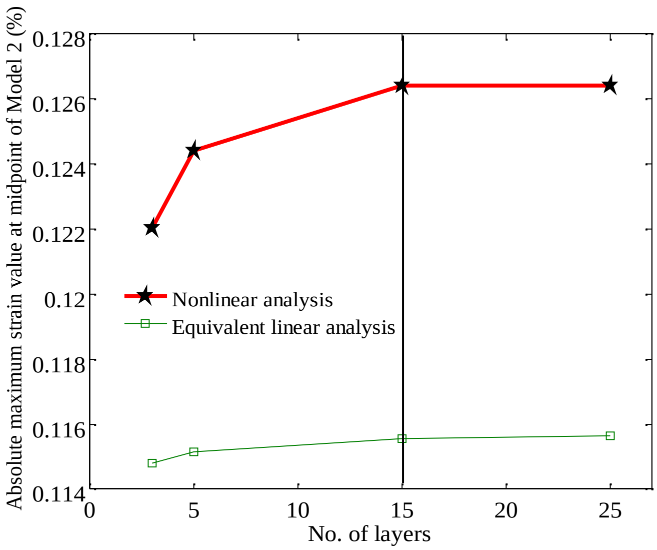
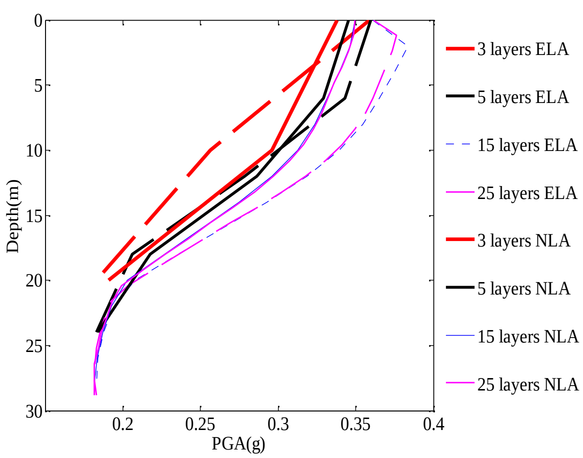


Fig. 5. Absolute maximum strain value at midpoint of layers against no of layers for Model 2

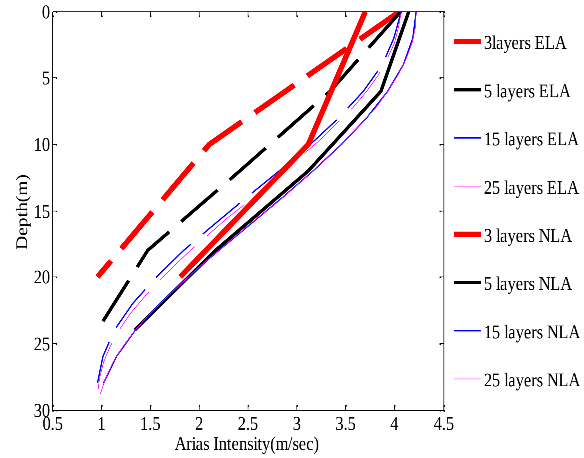
The PGA variation along the depth is shown in Fig. 6(a) for both ELA and NLA. From the result it has been observed that the PGA value at any depth is higher in ELA compared to that NLA [3]. This is because of evolution of EPWP in the model, which was considered in the NLA.

The earthquake energy also can be expressed in terms of Arias Intensity (AI) [5]. This AI can be represented as damage potential of an earthquake [16]. The amplification of AI along depth for ELA and NLA are shown in Fig. 6(b). Larger amplification in AI was observed for NLA compared to that in ELA. So due to generation of EPWP the damage potential is more in NLA, than that in ELA.

The seismic performance of heterogeneous soil was also compared with homogeneous soil results. The variation in PGA along depth for all analytical models for ELA and NLA are shown in Fig. 7(a) and 7(b).

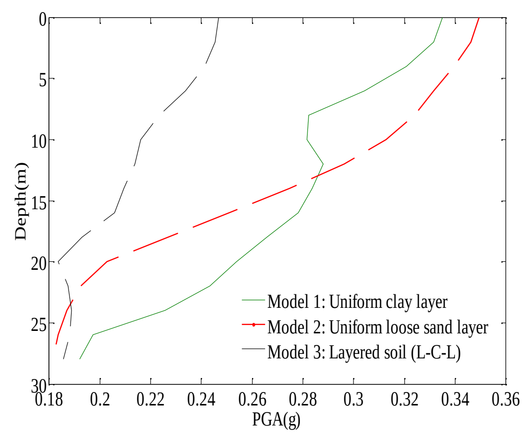


(a)

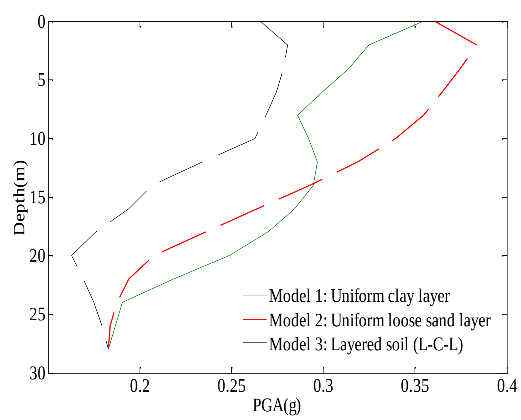


(b)

Fig. 6. (a) PGA profile against depth for Model 2 (uniform sand layer) with various layer thickness, (b) Arias intensity against depth for Model 2 (uniform loose sand) with various layer thickness



(a)



(b)

Fig. 7. (a) PGA profile against depth for nonlinear analysis on all soil models, (b) PGA profile against depth for equivalent linear analysis on all soil models

After comparison of results in Fig. 7, it is concluded that due to generation of EPWP in NLA the soil layer are softened and the seismic energy on those layer are less amplified than

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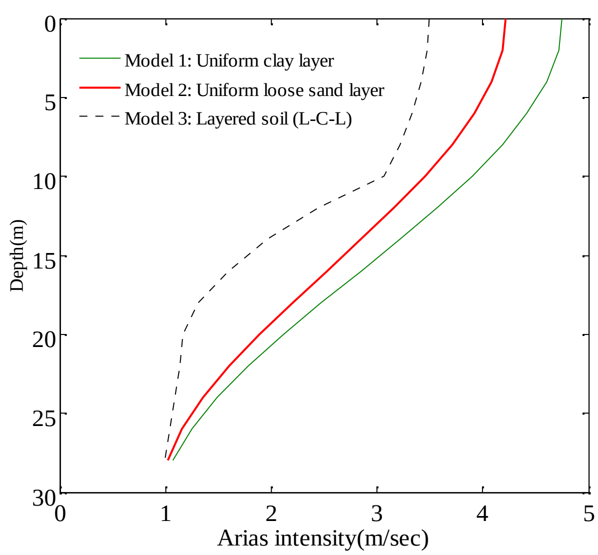
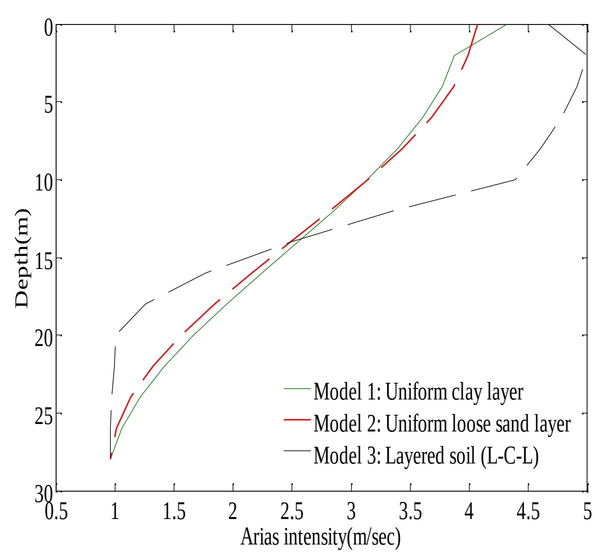
that in ELA. It can also be observed from these figures that the amplification is higher in homogenous soil model as compared to that in heterogeneous soil. One most important reason behind this is that the EPWP generation is more in heterogeneous soil than that in homogenous soil which causes more softening of heterogeneous soil layers [5].

Further, the arias intensity profiles for all numerical models are also presented for both ELA and NLA analyses. From Fig. 8(a) and 8(b) it is observed that ELA predicts more seismic energy migration compare to that predicted by NLA. It is also observed that NLA predicts lower seismic energy migration for heterogeneous soil model than homogenous soil model. The reason behind it could be the generation of pore pressure is more in layered soil which causes soil softening and resulted into less seismic energy migration in the above soil layer [17, 18]. In general soil is saturated below the water table. Therefore, it is concluded that the NLA represents more realistic soil seismic behavior.



(a)



(b)

Fig. 8. (a) Arias intensity profile against depth for nonlinear analysis on all soil models, (b) Arias intensity profile against depth for equivalent linear analysis on all soil models

From the comparison between PGA and AI in the Figures 7 and 8, it is observed that the effect of soil softening is more clearly visible in the AI profile in heterogeneous soil than that in homogenous soil. This supported previous conclusion that AI is better representation of seismic energy migration than PGA [19].

VI. CONCLUSION

The following are concluded from the numerical analysis of the homogeneous and heterogeneous soil model-

- Equivalent linear analyses predict more PGA amplification than nonlinear analysis for a soil layer. This is because evolution of EPWP was considered in the model in NLA. Due to generation of EPWP softening of soil occurs, which ultimately causes lower amplification in that soil layer.
- The soil heterogeneity affects the amplification in a soil layer. More EPWP generates in the heterogeneous soil than homogenous soil due to water film generation between two layers with various permeability. As more EPWP generates, more softening occurs in heterogeneous soil which produce less PGA and AI amplification in heterogeneous soil.
- The Arias Intensity is the better representation of seismic response than the PGA, theoretically and analytically. Theoretically it was already concluded that the Arias intensity represents the whole acceleration time history whereas PGA represents one single value (the peak value) of the acceleration time history. The AI migration along depth presented here more clearly shows the effect of soil softening in heterogeneous soil than that in homogenous soil. So, it supported the earlier conclusion that AI is better representation of seismic energy migration than PGA.

The nonlinear analysis gives more accurate result and the pore pressure generation and dissipation are calculated. But, the estimation of nonlinear properties and selection of curve fitting parameters are quite difficult and time consuming. Proper selection of nonlinear curve fitting parameters can be done with proper experience of seismic analysis on various types of soil.

Further research can be done on heterogeneous soil to determine the seismic response and comparison between analytical and experimental results. This will give more clear idea about the seismic behavior of heterogeneous soil and also it will give more reliability of the software used in the analysis.

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